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(6) Irradiation Effects on Fatigue Crack Propagation in Austenitic Stainless Steels.

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The effects of fast neutron irradiation on subcritical crack propagation in austenitic stainless steels are reviewed with respect to the influence of irradiation and test temperatures, neutron fluence, hold time effects, and thermomechanical history. Predictive methods for estimating crack propagation performance are discussed.

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CONTENTS

IRRADIATION EFFECTS ON FATIGUE CRACK PROPAGATION IN AUSTENITIC STAINLESS STEELS

INTRODUCTION

The austenitic stainless steels are being extensively utilized as structural materials in fast breeder reactors (FBR). In particular, these steels have been chosen for both in-core and out-of-core applications, such as piping and core support. Since it is recognized that the service conditions of breeder reactor systems will subject the structural components to cyclic loads at sustained elevated temperatures, the effects of fast neutron irradiation on the fatigue crack propagation performance of these steels must be known to the designer and safety analyst.

The purpose of this report is to review the experimental results concerning the effects of fast neutron irradiation on fatigue crack propagation performance of the austenitic stainless steels. Sufficient data are available to assess the trends in performance on irradiation temperature, neutron fluence, thermomechanical history, and test parameters, such as hold time. No attempt will be made to describe in detail those physical mechanisms responsible for the observed effects. Predictive methods being developed for estimating material performance will be briefly discussed.

EXPERIMENTAL RESULTS

The effects of fast neutron irradiation on the crack propagation in austenitic stainless steels have not been extensively investigated. Only recently has considerable emphasis been placed on the knowledge of fatigue crack propagation performance in neutron irradiated austentitc stainless steels for design and safety analysis purposes. It is likely that this increased emphasis is the direct result of the recognition that these materials may suffer significant toughness degradation during neutron irradiation (1,2) coupled with the growing likelihood that crack propagation performance of austenitic steels will be incorporated into the high temperature design codes.

The techniques of linear-elastic fracture mechanics (LEFM) have been successfully applied to relate the crack

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growth rate to the stress intensity factor in austenitic stainless steels according to the general expression:

$$da/dN = C(\Delta K)^m \qquad (1)$$

Although a somewhat different form of this expression to account for stress ratio effects may have greater utility for structural analysis purposes, Eq. 1 has been shown to satisfactorily describe the crack propagation behavior of the austenitic stainless steels under a wide variety of parametric conditions, including neutron irradiation. The general effects of these many parameters on fatigue crack propagation in austenitic stainless steels have been reviewed recently by James (3).

The available results for the effects of fast neutron irradiation on fatigue crack propagation at elevated temperatures in the austenitic stainless steels are rather limited (4-9). However, the results all indicate that parameters such as neutron fluence, irradiation and test temperatures, hold time, and thermomechanical history may have an important influence on crack propagation performance. These effects have been summarized by Michel and Korth (10).

The results from those studies which have been conducted to investigate the effects of fast neutron irradiation on crack propagation in austenitic stainless steels are shown in Figs. 1-6 for annealed, cold worked, and weld materials, respectively. All results shown in Figs. 1-6 were irradiated to the indicated fluences at temperatures from 400 to 500°C in EBR-II, except for those specimens irradiated to 0.18 n/cm^2 at 288°C in a thermal neutron environment. In Fig. 7, selected results for unirradiated annealed, and cold worked 316 stainless steel are shown for comparison purposes. The effects of hold time on crack propagation in neutron irradiated, 20 percent cold worked Type 316 steel are shown in Fig. 8.

Annealed Austenitic Stainless Steels

The results in Figs. 1 and 2 for annealed Types 304 and 316 steel illustrate the effects of neutron fluence and test and irradiation temperature on crack propagation as a function of stress intensity factor range. The results show that, for tests conducted at 427°C, an increase in neutron fluence from approximately 1 to 5 x 10^{22} produced no significant change in the rate of crack propagation with increased ΔK value. Note, however, the decreased crack propagation rate for the thermal neutron irradiated material at ΔK values ≤ 40 MPa$\sqrt{m}$. For tests at 593°C, the increase in test temperature produced a significant increase in

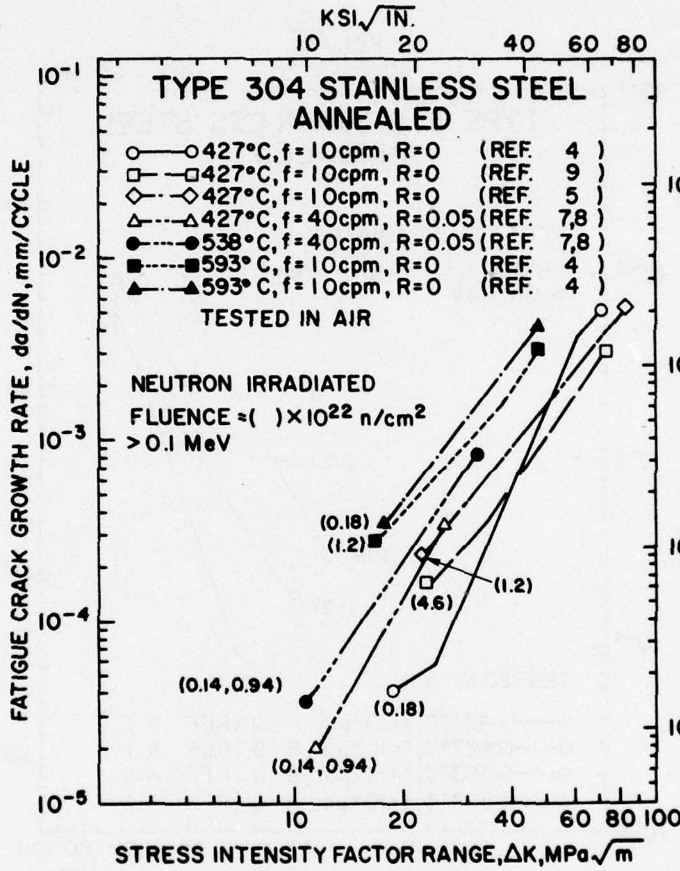

Fig. 1 — Postirradiation fatigue crack propagation performance of annealed Type 304 stainless steel

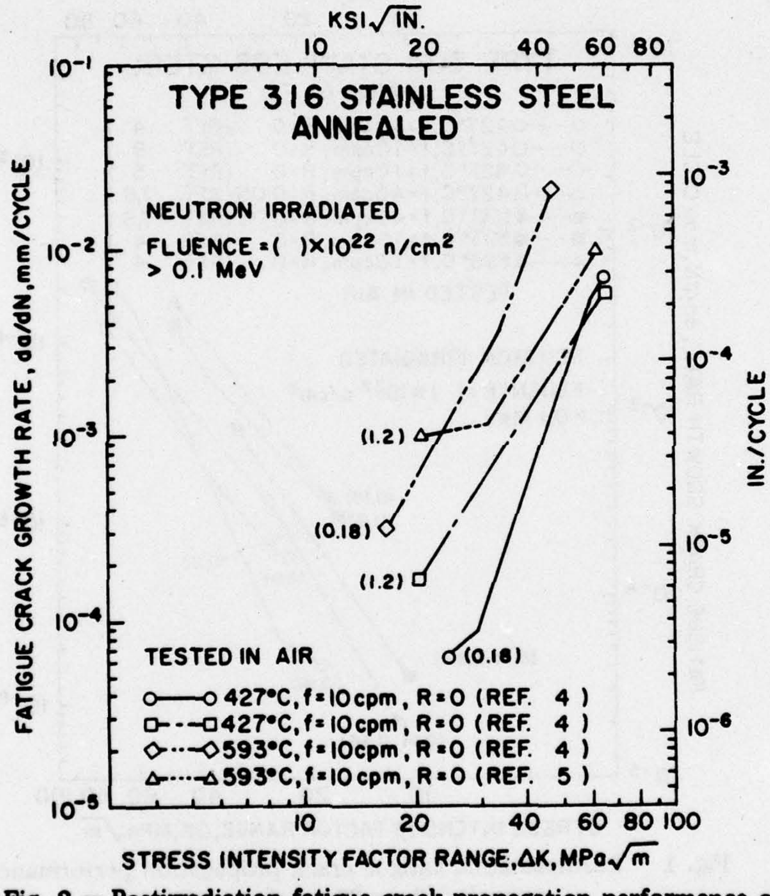

Fig. 2 — Postirradiation fatigue crack propagation performance of annealed Type 316 stainless steel

crack propagation rate at all values of ΔK when compared with the neutron irradiated material tested at 427°C. Again, it is of interest to note the somewhat larger increase in the crack propagation rate with the increased test temperature for the thermal neutron irradiated material when compared with the fast neutron irradiated material.

Comparison of the results in Figs. 1 and 2 with the unirradiated results in Fig. 7 shows that neutron irradiation to fluences from approximately 1 to 5 x 10^{22} n/cm^2 produced no substantial change in the rate of crack propagation for tests at 427°C. However, at test temperatures of 593°C, a small but significant increase in crack propagation rate is evident in the annealed, irradiated steels when compared with the unirradiated results.

Cold Worked Austenitic Stainless Steels

Figures 3 and 4 summarize the available results for crack propagation in cold worked austenitic stainless steels. For tests conducted at 427°C, the results indicate that the effect of increased neutron fluence is to increase the crack propagation rate at ΔK values $\leq$40 MPa$\sqrt{m}$., with nearly identical crack propagation rates at higher ΔK values at all fluences. At 593°C, the effect of increased test temperature is to increase the crack propagation rates by a factor of nearly 20 over the rates observed at 427°C for equivalent ΔK values.

Comparison of Figs. 3 and 4 with the unirradiated results in Fig. 7 shows that there is little effect of either neutron irradiation or cold work on crack propagation rate in Type 304 and 316 steel at 427°C. At a test temperature of 593°C, however, the results in Fig. 7 indicate that the crack propagation rate in the unirradiated steels is noticeably higher in the cold worked material than in the annealed material at equivalent ΔK values. Comparison of the cold worked results at 593°C in Figs. 3 and 4 with the unirradiated results in Fig. 7 indicates that the increase in crack propagation rate produced by neutron irradiation is significant, even at the lowest fluences, and results in a factor of approximately 10 increase in crack propagation rate at fluences of 1.2 to 1.4 x 10^{22} n/cm^2.

Austenitic Stainless Steel Welds

The available results for the effects of neutron irradiation on crack propagation in austenitic stainless steel welds are shown in Fig. 5 and 6. The results for Type 316 welds, although extremely limited, suggest that there is little effect of test temperature on crack propagation rate

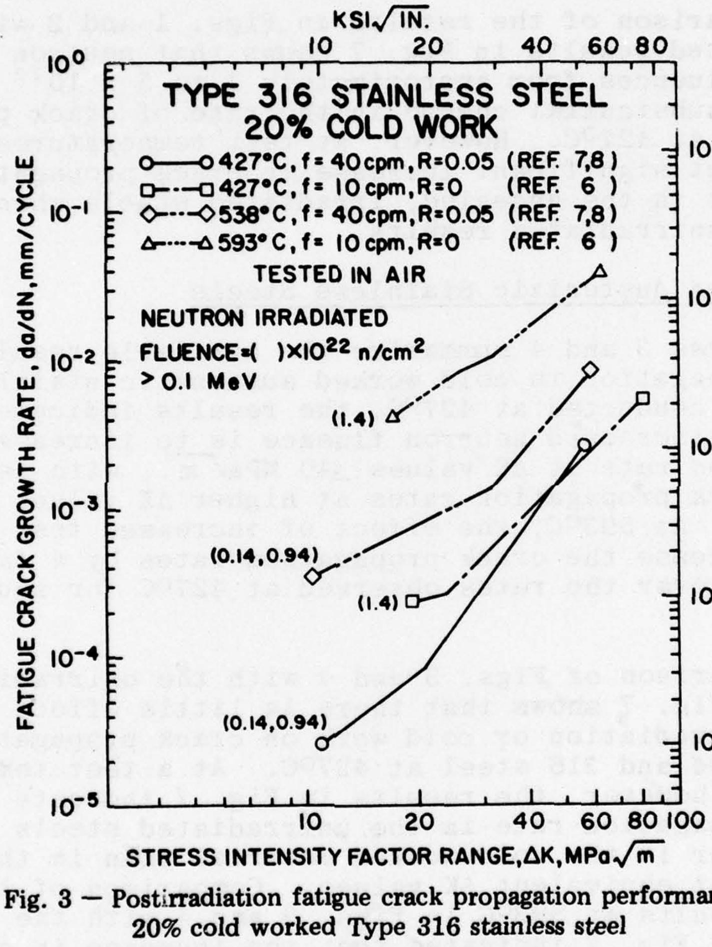

Fig. 3 — Postirradiation fatigue crack propagation performance of 20% cold worked Type 316 stainless steel

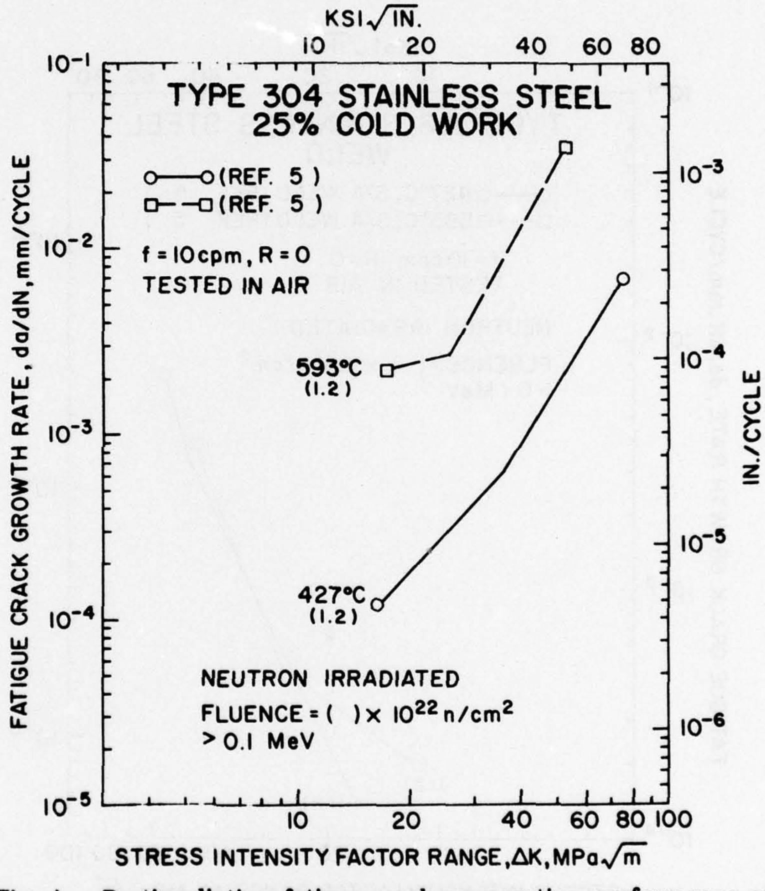

Fig. 4 — Postirradiation fatigue crack propagation performance of 25% cold worked Type 304 stainless steel

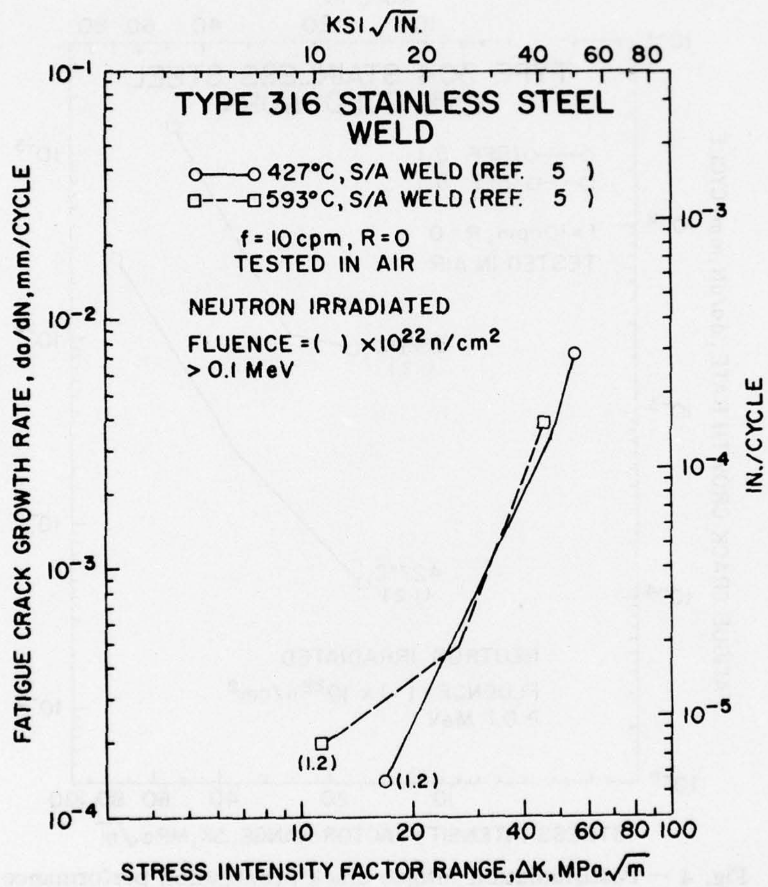

Fig. 5 — Postirradiation fatigue crack propagation performance of Type 316 *stainless steel weld*

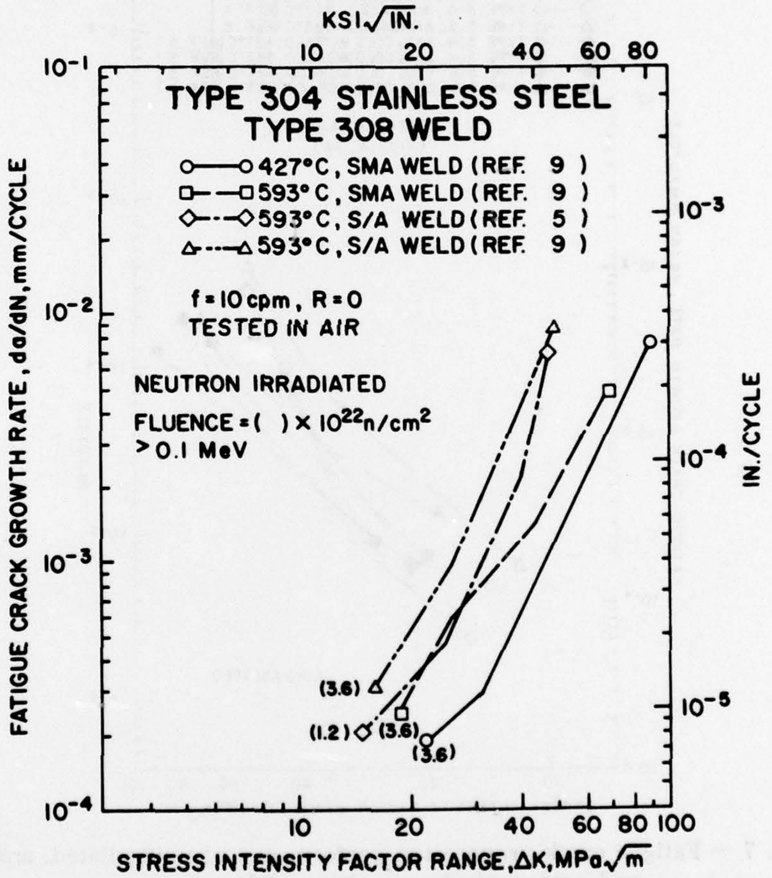

Fig. 6 — Postirradiation fatigue crack propagation performance of Type 308 stainless steel weld

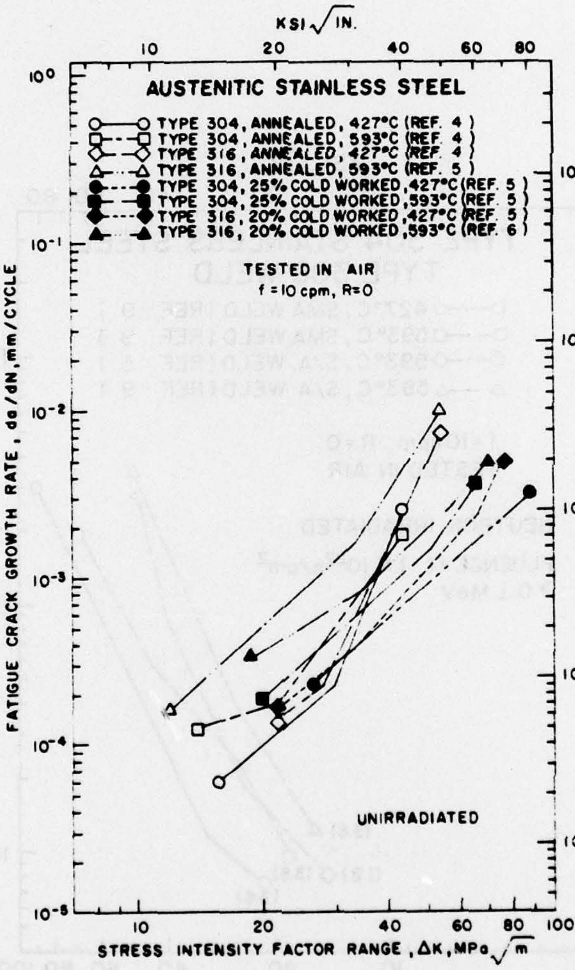

Fig. 7 — Fatigue crack propagation performance of unirradiated, annealed and cold worked austenitic stainless steels

for neutron irradiation to 1.2×10^{22} n/cm^2, Fig. 5. For the Type 308 welds, inspection of Fig. 6 shows that an increase of neutron fluence from 1.2 to 3.6×10^{22} n/cm^2 produced an increase in crack propagation rate at all values of ΔK for submerged-arc (S/A) welds at 593°C. However, comparison of the S/A and the shielded metal arc (SMA) weld results, irradiated to 3.6×10^{22} n/cm^2 and tested at 593°C, suggests that the crack propagation resistance of the SMA weld may be superior at all values of ΔK.

Comparison of the irradiated weld results in Fig. 6 with similarly tested unirradiated weld material (9) shows that, at 593°C, neutron irradiation to 1.2×10^{22} n/cm^2 has little apparent effect on crack propagation rate in Type 308 S/A welds. Following irradiation to 3.6×10^{22} n/cm^2, however, there appears to be a significant reduction in the crack propagation resistance of the S/A weld at 593°C when compared wtih unirradiated weld material. In contrast with these results, the results for the SMA welds irradiated to 3.6×10^{22} n/cm^2 show a negligible effect of neutron irradiation when compared with unirradiated, thermally aged SMA welds tested at both 427 and 593°C (9).

Hold Time Effects

The effect of tensile hold time on elevated temperature crack propagation in neutron irradiated Type 316 stainless steel has been investigated by Michel et al. (6). Their results show that, at 427°C, the addition of tensile hold times of up to 1 minute, at the maximum load portion of the fatigue cycle, produced a negligible increase in crack propagation rate in both annealed and cold worked, irradiated and unirradiated material. At test temperatures of 593°C, however, the effect of hold time was to produce a small but significant increase in crack propagation rate in annealed, neutron irradiated material when compared with unirradiated results. For 20 percent cold worked material, their results in Fig. 8 show a significant increase in crack propagation rate with increased hold time in both irradiated and unirradiated material. Note the approximate order of magnitude increase in crack propagation rate when comparison is made between irradiated and unirradiated tests at equal hold times in Fig. 8.

DISCUSSION

In this report, the available experimental results concerning the primary effects of fast neutron irradiation on fatigue crack propagation in the austenitic stainless steels have been presented. It is seen that under conditions where the irradiation and test temperatures are approximately

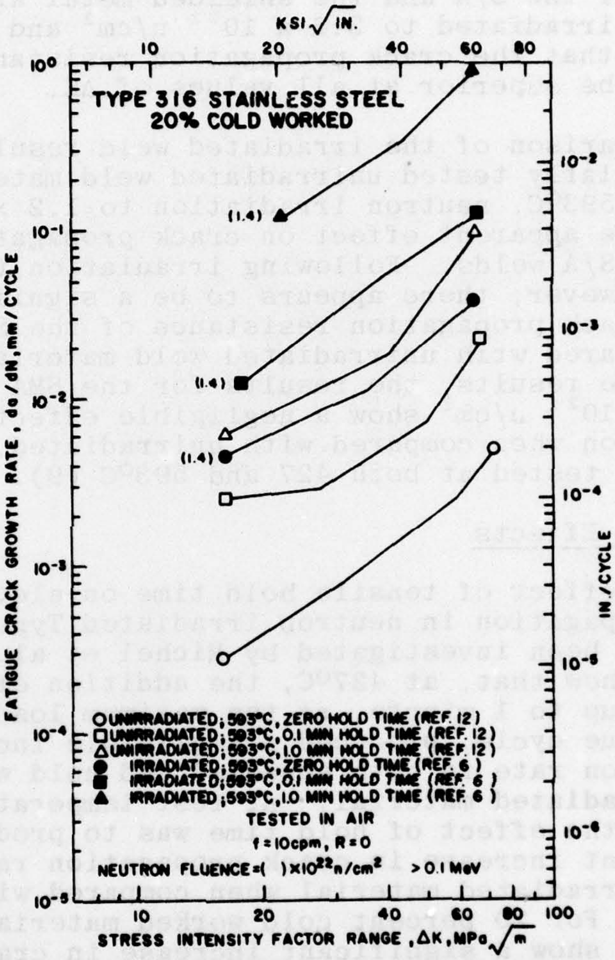

Fig. 8 — Effect of hold time on fatigue crack propagation performance of neutron irradiated and unirradiated, 20% cold worked Type 316 stainless steel

equal near 427°C, neutron irradiation has no significant effect on the rate of crack propagation. However, at a test temperature of 593°C, it is seen that the crack propagation rate after neutron irradiation is higher than for unirradiated material. These differences in crack propagation performance have been discussed by the original investigators in terms of various factors which may influence crack propagation. These factors include the microstructural effects of neutron irradiation, test temperature, specimen thermomechanical history, hold time and/or frequency, and test environment.

Michel, Smith and Watson (6) have addressed the interrelated effects of test temperature, neutron irradiation, and thermomechanical history on specimen microstructure in the context of crack propagation. They concluded that the reduced ductiltiy produced by test temperatures higher than the irradiation temperature was primarily responsible for the increased crack propagation rates observed in the solution annealed and neutron irradiated Type 316 steel tested at 593°C. In the similarly irradiated and tested cold worked material, they concluded that the thermally-activated, time-dependent recovery of the cold work combined with the reduced ductility due to neutron irradiation was responsible for the greatly increased crack propagation rates.

James (8) also has recognized that the reduced ductilities could influence crack propagation when test temperature exceeds irradiation temperature. He noted that the reduced ductilities at higher temperatures also could be influenced by the generation of helium by various (n,α) reactions. Since it is known that thermal neutrons produce significantly more helium than fast neutrons, it would be expected that increased test temperature would produce proportionately higher crack propagation rates in thermal neutron irradiated material than in fast neutron irradiated material. It is likely that this effect is responsible for the increased crack propagation rates noted in Figs. 1 and 2 for the thermal neutron irradiated Types 304 and 316 steels tested at 593°C when compared with the fast neutron irradiated materials tested at this same temperature. This suggests that the influence of (n,α) generated helium may have an even more pronounced effect on fatigue crack propagation when the quantity of helium is dramatically increased above the levels experienced in fast reactor environments. Such situations are expected to occur in controlled thermonuclear reactors (CTR).

The influence of neutron irradiation and elevated temperature crack propagation on the microstructure of annealed Type 316 austenitic stainless steel has been examined by

Michel and Smith (11). Their results indicate that the dislocation substructure in unirradiated material at both 427 and 593°C was limited to the region within about 1 mm of the crack surface. The effective stress levels deduced from the substructure results were higher at 427°C than at 593°C in agreement with the higher levels of ΔK at 427°C. No evidence of dislocation cell formation was observed in neutron irradiated specimens at distances greater than 0.75 mm from the crack surface. Although not discussed by Michel and Smith, these results further demonstrate the effect of reduced ductility produced by the neutron irradiation to directly influence the crack propagation performance of the austenitic stainless steels.

The influence of hold time effects in fast neutron irradiated Type 316 steel was examined by Michel et al. (6). In the discussion of their results, they analyzed the hold time data on the basis of crack propagation per unit time, da/dt, in order to obtain additional insight into whether time-dependent (creep) and/or environmental effects contributed to crack propagation rate. The analysis also examined the experimental results on the basis of fractional cycle time, where the load exceeded 50 percent of the maximum cyclic load, t*, and on the basis of time at maximum static load, t_s. They concluded that, for their tests at 427°C, thermally activated deformation processes did not contribute to the crack propagation behavior in either the unirradiated or neutron irradiated materials. However, based on their analysis of the test results at 593°C, which showed that the crack propagation rate per unit time, da/dt, was dependent on time at maximum static load and independent of hold time, it was determined that the annealed, unirradiated material represented the basic material behavior where no significant effect of hold time on crack propagation rate was found. With the addition of cold work and/or neutron irradiation, it was found that the effect of hold time to increase crack propagation rate resulted from thermally activated, time-dependent recovery of the cold work microstructure and the reduced ductility produced by the irradiation. For hold times longer than 1 minute, Michel et al. (6) concluded that creep-assisted crack propagation was *more* likely. Their results for 20 percent cold worked, unirradiated Type 316 steel at 593°C show that the crack propagation rate is increased by a factor of approximately 30 when a 10 minute static hold time was included in the fatigue cycle. Recent results by Shahinian (12) also have confirmed that crack propagation rate in 20 percent cold worked, unirradiated Type 316 steel is increased by a 10 minute hold time during testing. Michel et al. (6) also examined the relationship between hold time and cyclic frequency. Their results for 20 percent cold worked, unirradiated Type 316 steel show equivalent crack proapgation rates during separate tests at 593°C for a 0.1 minute hold time and for continuous cycling at 5 cpm (0.085 Hz). However, based on an analysis of the results, they concluded that the mechanisms which control crack propagation during hold time and during continuous cycling at the same frequency are not necessarily the same.

It is well known that test environment can have a pronounced effect on fatigue crack propagation behavior in austenitic stainless steel (13). However, since all reported tests on neutron irradiated specimens have been conducted in an air environment, no information is presently available concerning the relative effects of vacuum or inert environment on crack propagation in irradiated material. In unirradiated material, Michel et al. (6) have discussed the effects of environment on their hold time results. Based on calculations of the critical oxygen pressure, they concluded that all crack surfaces were saturated with oxygen immediately upon formation and that the hold time effects which they observed were not the result of an environmental frequency effect. In unirradiated, annealed Type 304 stainless steel, James and Knecht (14) have shown that the crack propagation rate in vacuum and liquid sodium environments at 427°C is similar to that in air at room temperature and lower than that in air at 427°C. Based on these results, James and Knecht questioned the existence of a thermally-activated creep component during elevated temperature crack propagation in air and suggested that the enhancement in crack propagation may result from the influence of oxygen. However, no hold time tests were conducted by James and Knecht to investigate this possibility in inert environments. James (15) also has discussed these points further in subsequent work where it was concluded that elimination of the air environment has the effect of greatly suppressing the thermally-activated, time-dependent effects which are generally attributed to creep. Speidel (16) has noted that the effects of an air environment on crack propagation at elevated temperature represent a phenomenological analog to that observed at lower temperatures for corrosion fatigue. He attributes the close coupling between the two phenomena to the aggressive effects of the air environment at low cyclic frequencies at elevated temperatures. Speidel also noted that the crack propagation rate is between two and three times higher in air than in vacuum at elevated temperatures for many materials. Since it also has been noted (6) that the environmental effect of air at room temperature on crack propagation rate in Type 348 stainless steel is of the same order of magnitude as that as 228°C, it remains to be determined whether the apparent thermally-activated, component of elevated crack propagation is entirely the results of an environmental effect or whether a true time-dependent creep mechanism is operative as well. However, it would be expected that, with increased temperatures in the range from 0.4 to 0.7 T_m in the austenitic stainless steels, the likelihood of a true creep mechanism to influence crack propagation will be increased. In neutron irradiated material, it is reasonable to believe that the environment would have nearly the same effect on crack propagation performance as in unirradiated material since the environment is primarily an external, surface effect. On the other hand, if a true time-dependent creep mechanism is operative during hold time, for example, it is expected that the crack propagation in the neutron irradiated material would proceed at a faster rate than in the unirradiated material. This is suggested by the results in Figs. 1-6 and by the available results concerning the effects of irradiation on creep and tensile ductility in these steels (17) which show that, in the thermal creep range, ductility loss results from a combination of matrix hardening and helium embrittlement. At the present time, there is no reason to conclude that crack propagation would not be influenced by neutron irradiation to any lesser extent than are the other mechanical properties. A direct indication of this influence is evident from the previously discussed substructure (11) results for the irradiated and unirradiated crack propagation specimens.

The application of parametric methods to predict the crack propagation performance of austenitic stainless steels has received relatively little attention and no work has been done for irradiated stainless steels. Carden (18,19) recently has proposed at least two such parameters to account for the effect of temperature and frequency on elevated temperature crack propagation in unirradiated materials. These parameters represent some success toward the combination of various effects on crack propagation into a single, empirical relationship. The lack of a firm physical basis, however, is a distinct drawback to the potentially useful nature of these parameters.

The development of any predictive method of elevated temperature crack propagation in the austenitic stainless steels must include an account of the temperature dependent of strength properties, the influence of microstructure, and the ability of the material to undergo cyclic work hardening or softening. The influence of environment and the effects of neutron irradiation on physical properties must be included as well. Consideration of these factors shows that only the effect of environment is a property of the material which is not related to basic physical behavior. Therefore, environment effects must be considered separately.

Among the basic physical properties of materials which reflect the influence of these factors are the various parameters such as the elastic, bulk and shear moduli. Of these moduli, however, only the elastic modulus represents the basic elastic behavior, and several attempts (30,31) have been made to use it to correlate crack propagation results computed using fracture mechanics procedures for unirradiated materials tested at temperatures up to 593°C.

Speidel (16) has employed the modulus of elasticity to correlate the fatigue crack propagation rates of numerous materials in vacuum and concluded that the elastic modulus was a materials parameter of primary importance for vacuum environments. As previously noted, Speidel found that the crack propagation rate in air was two to three times higher than in vacuum. By employing a factor of three correction for the air environment and correcting the modulus of elasticity for temperature variations, he was able to show a good correlation between predicted and experimentally measured crack propagation rates at frequencies down to ~1 Hz. Although the correlation also represents an empirical relationship, it appears to show promise as a method for employing a unifying basic materials parameter to predict fatigue crack propagation.

In order to evaluate the use of the elastic modulus as a parameter to correlate the neutron irradiated crack propagation results for the austenitic stainless steels, the 593°C results for annealed Types 304 and 316 steel from Figs. 1 and 2 were normalized by dividing the stress intensity factor range by the temperature compensated elastic modulus for each respective steel using the modulus values reported in the Nuclear Systems Materials Handbook (22). These values were further corrected for the effects of irradiation using the values reported by Tantrow (23) for Type 304 material. The normalized results are compared in Fig. 9 with unirradiated data for these steels, previously reported by Michel and Smith (24), after normalization by the same unirradiated elastic modulus values. Figure 9 illustrates that the crack propagation rates for both materials in the irradiated and unirradiated conditions are well correlated on the basis of the normalized stress intensity factor range. The figure also demonstrates that the elastic modulus does exhibit promise as a parameter for use in correlating neutron irradiated results for the prediction of fatigue crack propagation performance in the austenitic stainless steels. However, considerable additional research will be necessary to incorporate the complex interactions between material, environmental and mechanical properties and to assess whether the elastic modulus or other possible parameters provide the best correlation of the neutron irradiated results.

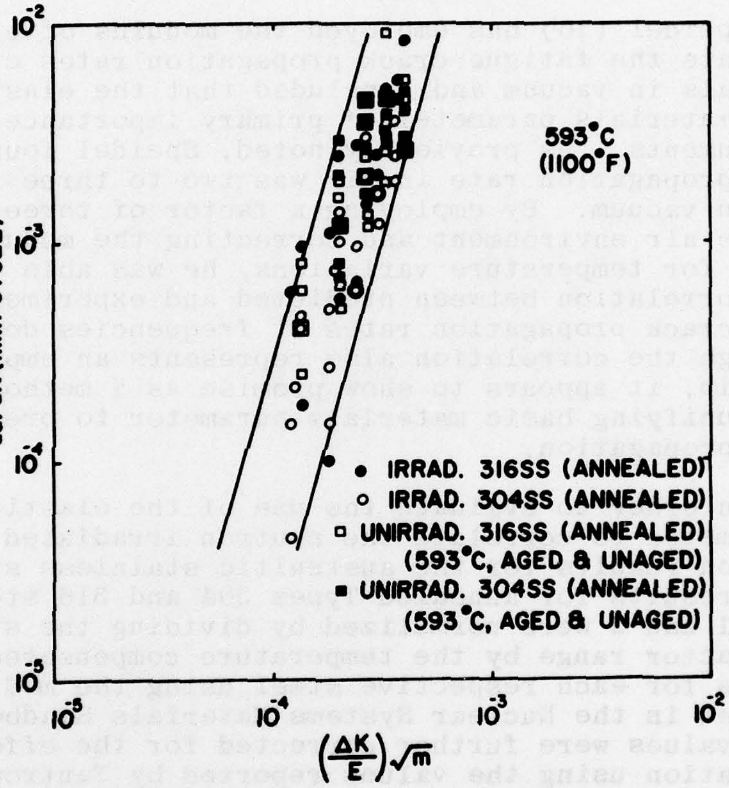

Fig. 9 — Dependence of fatigue crack propagation rate of neutron irradiated and unirradiated austenitic stainless on elastic modulus compensated stress intensity factor range

SUMMARY AND CONCLUSIONS

The available results concerning the effects of fast neutron irradiation on the fatigue crack propagation behavior of austenitic stainless steels has been reviewed. The following conclusions are drawn from this review:

1. Neutron irradiation up to fluences of 5×10^{22} n/cm^2 produced no significant effect on crack propagation rate of annealed austenitic stainless steels in air when the test temperature (427°C) is within ±50°C of the irradiation temperature.

2. The increase in test temperature to 593°C produces a small increase in crack propagation rate in annealed austenitic stainless steel when compared with unirradiated tests at 593°C.

3. The effect of increased neutron fluence up to 5×10^{22} n/cm^2 is to produce a small increase in crack propagation rate of cold worked austenitic stainless steels at ΔK values ~40 MPa$\sqrt{m}$ at 427°C. Comparison with unirradiated results, however, indicates that there is no significant effect of neutron irradiation at 427°C on crack propagation rate in the cold worked steels.

4. An increase in test temperature of the cold worked, neutron irradiated steel from 427 to 593°C results in a substantial increase in crack propagation rate which exceeds the increase produced in unirradiated material by the equivalent increase in test temperature.

5. Results for Type 308 welds indicate that an increase in fluence from 1.2 to 3.6×10^{22} n/cm^2 produces an increase in crack propagation rate for submerged-arc welds at 593°C as opposed to shielded-metal arc welds where no significant effect on crack propagation rate is observed.

6. Predictive methods of crack propagation performance are being investigated and several empirical parameters have been proposed. It was demonstrated that the elastic modulus provides a successful correlation between irradiated and unirradiated austenitic stainless steel fatigue crack propagation results.

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